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14. ABSTRACT

The Naval Research Laboratory (NRL) has tested and demonstrated a prototype moving-map system for naval landing craft and amphibious vehicles. NRL proposed that a moving-map would improve crew situational awareness and communications, thereby improving precise lane navigability. This paper presents results of demonstrations performed during the Transparent Hunter naval exercise in January 2003. Comparisons in navigation performance (measured in terms of root mean square "cross-track" error) are presented for vehicles using the moving-map system and the same vehicles using no moving-map. These results suggest that the moving-map significantly improves lane navigation performance. Crew feedback was also positive: crewmembers reported that the moving-map was easy to operate with minimal training and very effective in helping operators keep the vehicle within the lane.

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Demonstration of a Moving-Map System for Improved Precise Lane Navigation of Amphibious Vehicles and Landing Craft

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***Abstract* - The Naval Research Laboratory (NRL) has tested and demonstrated a prototype moving-map system for naval landing craft and amphibious vehicles. NRL proposed that a moving-map would improve crew situational awareness and communications, thereby improving precise lane navigability. This paper presents results of demonstrations performed during the Transparent Hunter naval exercise in January 2003. Comparisons in navigation performance (measured in terms of root mean square "cross-track" error) are presented for vehicles using the moving-map system and the same vehicles using no moving-map. These results suggest that the moving-map significantly improves lane navigation performance. Crew feedback was also positive: crewmembers reported that the moving-map was easy to operate with minimal training and very effective in helping operators keep the vehicle within the lane.**

I. INTRODUCTION

The Naval Research Laboratory (NRL) has tested and demonstrated a prototype moving-map system on naval Landing Craft Utility (LCU) and Amphibious Assault Vehicles (AAV) to aid navigation around mines and obstacles in the surf and beach zones. The moving-map selected for these demonstrations consists of an inexpensive commercial Windows-based PC running government off-the-shelf (GOTS) software.

For both the LCU and AAV, one crewmember is responsible for navigation while another steers the vehicle. In both cases, communication among crew-members is vital for successful navigation, yet considerably hampered by the fact that they are located remotely from one another. A moving-map system was expected to improve communications, facilitate shared situational awareness (SA) among crewmembers, improve their ability to precisely navigate assault lanes, and ultimately reduce the requisite lane width.

The section following this introduction presents a brief background on current navigation procedures for LCU and AAV platforms and a description of the moving-map system used for the demonstrations. A methods section, which describes the moving-map test procedures used during Transparent Hunter 2003 (TH03) trials, is followed by test results and conclusions. Table 1 provides a list of acronyms and abbreviations used throughout this paper.

TABLE 1. ABBREVIATIONS USED IN THIS PAPER

AAV	Amphibious Assault Vehicle
ARVCOP	Augmented Reality Visualization for Common Operation Picture
AVTB	Amphibious Vehicle Test Base
CM	Craftmaster
CSS	Coastal Systems Station
CTE	Cross-Track Error
DGPS	Differential Global Positioning Satellite
GeoTIFF	Geographic Tagged Image File Format
GOTS	Government Off-The-Shelf
GPS	Global Positioning Satellite
LCAC	Landing Craft Air Cushioned
LCU	Landing Craft Utility
MIREM	Mine Warfare Readiness and Effectiveness Measuring
MM	Moving Map
NIMA	National Imagery and Mapping Agency
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
ONR	Office of Naval Research
PC	Personal Computer
PLGR	Precision Lightweight GPS Receiver
SA	Situational Awareness
TH03	Transparent Hunter 2003 Naval Exercise
TSI	Technology Services, Inc

II. BACKGROUND

A. Standard navigation procedures for LCU and AAV

The LCU (fig. 1) is operated by three crewmembers: navigator, craftmaster, and helmsman. The navigator and helmsman are stationed below decks with a limited outside view, while the craftmaster is situated topside with a 360° view of the surrounding area. The navigator provides range and bearing information to the craftmaster, who instructs the helmsman to make appropriate course corrections. All communication between the craftmaster and the other two crewmembers is accomplished via sound tube. The navigator has access to paper charts, radar, a gyrocompass and (in some cases) an electronic chart display. The craftmaster has a gyrocompass, but no charts or navigation displays.

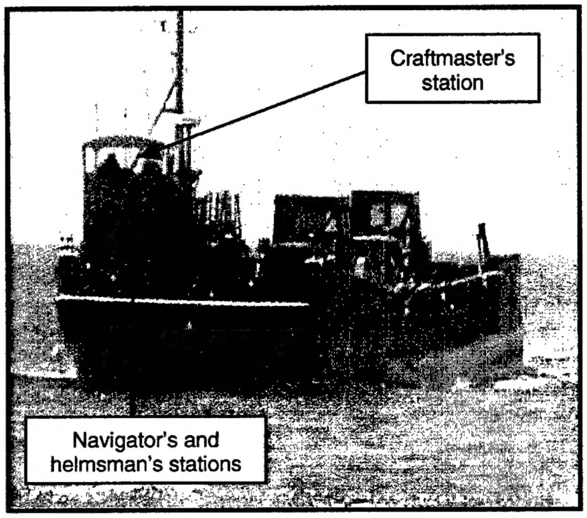

Fig. 1. Primary LCU crew locations

The AAV (fig. 2) is equipped with few navigational aids, and the crew has limited visibility from inside the vehicle. The crew chief uses a periscope – or intermittently pops the hatch – to improve visibility. The driver has limited visibility through small windows, which are often obscured by sea spray, so the driver must rely heavily on the crew chief for direction.

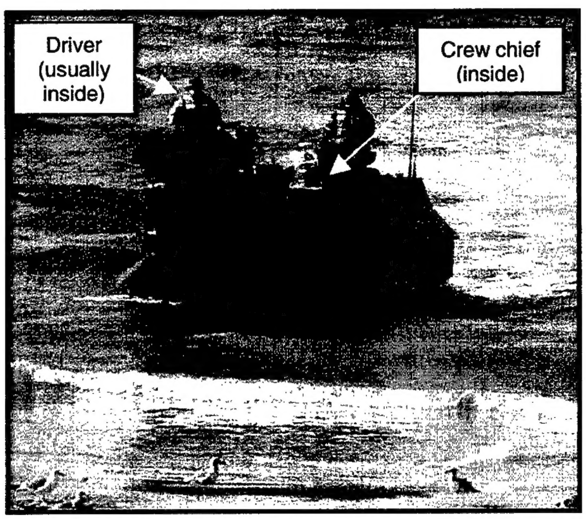

Fig. 2. Primary crew locations on an AAV.

In some cases, the crew chief is issued a Precision Lightweight Global Positioning System (GPS) Receiver (PLGR), which displays vehicle location as latitude and longitude coordinates on a small handheld device. The PLGR is not available on all AAVs, and most crew chiefs (including several who participated in our demonstrations) are unfamiliar with its operation. Many crew do not even carry a compass. Some AAVs may be equipped with a thermal imaging display in the future, but this is not installed in any vehicles to date. Communication between the driver and crew chief is via radio, but speech is often muffled by surrounding surf and engine noise.

B. NRL moving-map project for amphibious vehicles

In FY02, the Office of Naval Research (ONR) funded NRL Code 7440.1 to test and demonstrate a prototype moving-map system on LCU and AAV platforms in conjunction with a precise lane navigation study being conducted by the Coastal Systems Station (CSS) in Panama City, FL. For demonstration purposes, NRL selected the GOTS FalconView software, which is the moving-map module of the Portable Flight Planning System widely used by the Naval Air Systems Command for map and mission planning. FalconView is free of charge with no licensing restrictions within the U.S. Department of Defense. FalconView supports all standard digital map and chart products distributed by the National Imagery and Mapping Agency (NIMA) and National Oceanic and Atmospheric Administration (NOAA), as well as the Geographic Tagged Image File Format (GeoTIFF), providing virtually unlimited digital map and chart sources. FalconView provides both track-up and north-up orientations; simple graphical overlay capabilities (e.g., to superimpose battlefield geometry and lane boundaries on the underlying map display); a "breadcrumb trail" to represent the vehicle's track, and a smooth scroll function (such that the map moves beneath a stationary vehicle icon). Range and bearing information can be displayed as needed.

The prototype moving-map (MM) system hosts FalconView on relatively low cost, commercial off-the-shelf (COTS) hardware, including a rugged, water-resistant computer, monitors, and GPS or Differential GPS (DGPS) antenna and receiver. NRL utilizes existing computers and peripheral equipment on-board the test vehicles when possible, to minimize cost and space requirements. Fig. 3 shows the MM configuration for the LCU, and Fig. 4 depicts the display installed in the navigator's and craftmaster's stations. Both LCU crewmembers view the same information: both displays are linked to one PC, which is controlled by the navigator. Fig. 5 shows the MM configuration for the AAV, and Fig. 6 depicts the display installed in the AAV driver's station.

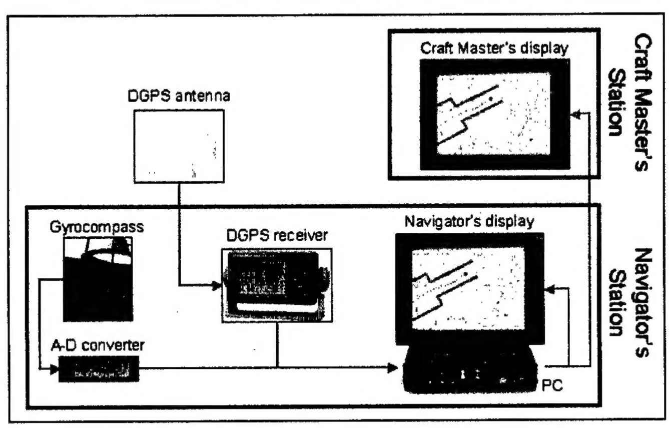

Fig. 3. LCU configuration of NRL-MM system.

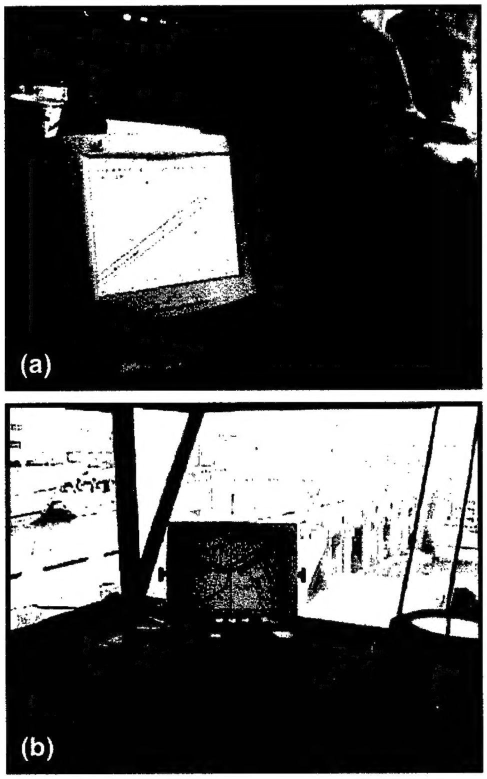

Fig. 4. NRL-MM displays installed in a LCU: (a) Navigator's station; (b) Craftmaster's station.

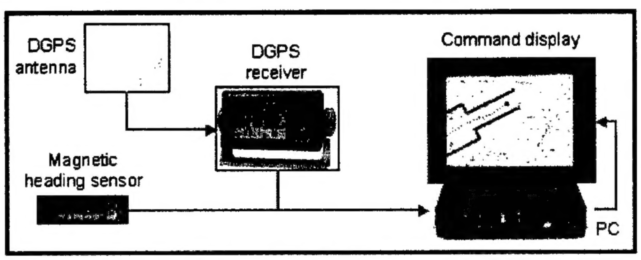

Fig. 5. AAV configuration of NRL-MM system.

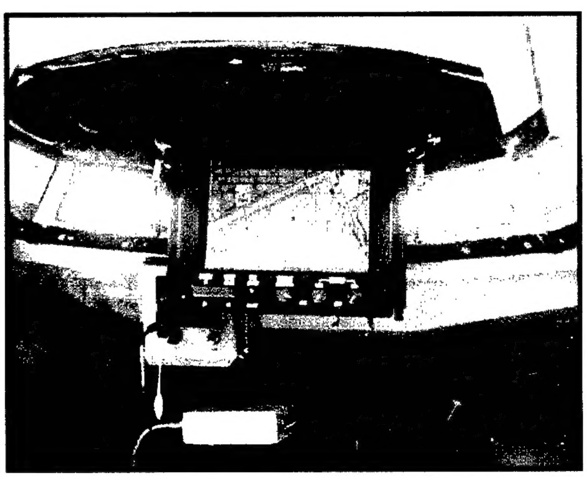

Fig. 6. View from inside the AAV, showing driver's station with NRL-MM display and windows to outside view.

C. Initial tests and demonstrations

NRL first tested the prototype MM on AAVs in May 2002 with the 3rd Platoon, Company A, 4th Assault Amphibian Battalion Reserve Unit at the CB Base in Gulfport, MS (Gendron, et al., 2002). Preliminary data from these tests (collected by both NRL and CSS) suggests that use of the MM improved lane navigation performance, compared with use of a PLGR. Crew feedback was also very positive: AAV crewmembers reported that the moving-map system was easy to operate with minimal training and very effective in helping operators keep the vehicle within the lane. As one operator put it, "This is a step in the right direction!"

Follow-on demonstrations were conducted on AAV, LCU, and Landing Craft Air Cushion (LCAC) platforms during Fleet Battle Experiment-Juliet at Camp Pendleton, CA (July 2002). Crewmembers provided several recommendations for improvement to the moving-map displays, including integration of an independent heading sensor to stabilize the map when the vehicle is motionless. Without any heading information coming from the GPS receiver, the map on a track-up display (or the vehicle icon on a north-up display) will spin, which crewmembers reported was annoying and temporarily disorienting.

In late FY02, ONR funded NRL to integrate a heading sensor with the moving-map display and test the resulting system on both LCU and AAV platforms. LCU tests were conducted at Little Creek, VA, in October 2002. During those tests, we determined that the magnetic heading sensor was ineffective on the LCU due to the abundance of metal on the craft. A far better (and less expensive) solution was to integrate the NRL-MM system with the LCU's own gyrocompass, via an analog to digital converter, which successfully eliminated the spinning display and improved crew situation awareness. Tests of the NRL-MM system with independent heading sensor were conducted on AAVs at Gulfport in October and the Amphibious Vehicle Test Base (AVTB) at Camp Pendleton in November 2002. During those tests, we determined that the magnetic heading sensor was effective on the AAV and successfully stabilized the map display.

Final tests and demonstrations of the NRL-MM system took place on LCU and AAV platforms during the Transparent Hunter 2003 (TH03) exercise in January. This paper presents navigation performance results and crew feedback from the LCU and AAV moving-map tests during TH03.

III. MM TEST PROCEDURES

During the TH03 MM demonstrations, NRL collaborated with a Mine Warfare Readiness and Effectiveness Measuring (MIREM) observation team from the Surface Warfare Development Group, which provided an inde-

pendent assessment of our experimental procedures and observations. Our experimental design called for comparing the current (or baseline) mode of operations for each craft with operations using the NRL-MM system to determine whether the moving-map could reduce the required width of assault lanes.

A. LCU MM Operations

The baseline mode of LCU operations called for the navigator to use a paper chart and verbally relay positional (range and bearing) information to the craftmaster, who then instructed the helmsman to make course corrections. In a second test, which is more similar to current LCU operations, the navigator referred to the MM display and again verbally relayed positional information to the craftmaster. In a third test, both the navigator and craftmaster used the MM display. The navigator still communicated with the craftmaster, but in this case, both crewmembers shared the same displayed information, which was assumed to improve communications and minimize navigational errors. In a fourth test, NRL collaborated with Technology Services, Inc. (TSI) in a joint demonstration of the MM system with TSI's Augmented Reality Visualization for the Common Operation Picture (ARVCOP), which overlays navigation data onto a ship pilot's field of view, displaying both navigational and tactical data on a bridge-mounted heads-up display. Based on a MIREM suggestion, NRL tested the MM at three geographic scales: 1:20k (k = thousand), 1:10k, and 1:5k (table 2).

TABLE 2. LCU MM TEST PLAN (SUMMARY)

Scale	Paper chart	Moving-map Nav only	Moving-map CM / Nav	Moving-map ARV-COP	Total runs
1:20k	4	3	6	4	**17**
1:10k	–	2	6	4	**12**
1: 5k	–	3	7	–	**10**
Total	**4**	**8**	**19**	**8**	**39**

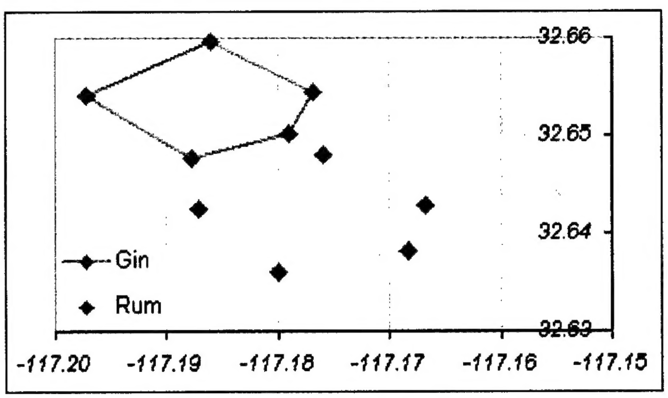

Fig. 7. LCU routes at Silver Strand, Coronado, CA

Two LCUs were planned for the trials, but one craft broke down on the first day and did not provide any data for this study. The remaining LCU completed 39 runs over three days. Two routes were used, depending on surrounding boat traffic (fig. 7). The routes were close together and identical in number of legs, approximate length of each leg, and turn angles. Runs were conducted randomly in both clockwise (CW) and counter-clockwise (CCW) directions.

B. AAV MM Operations

The baseline mode of AAV operations chosen for this study called for the crew chief to use a hand-held PLGR and relay positional information to the driver, who then made course corrections. For our comparison case, the driver could view the moving-map display directly, and the PLGR was not used. Based on a suggestion from the MIREM team, NRL tested three variations on the MM display during the AAV runs:

1) North-up map with moving icon (i.e., the icon representing the AAV moved across a fixed map);
2) Track-up map with moving icon;
3) Track-up moving map with stationary icon (i.e., the map moved, while the icon remained centered).

TABLE 3. AAV MM TEST PLAN (SUMMARY)

System configuration	# runs
PLGR	7
MM (North-up, moving icon)	4
MM (Track-up, moving icon)	4
MM (Track-up, moving map)	4
Total runs	**19**

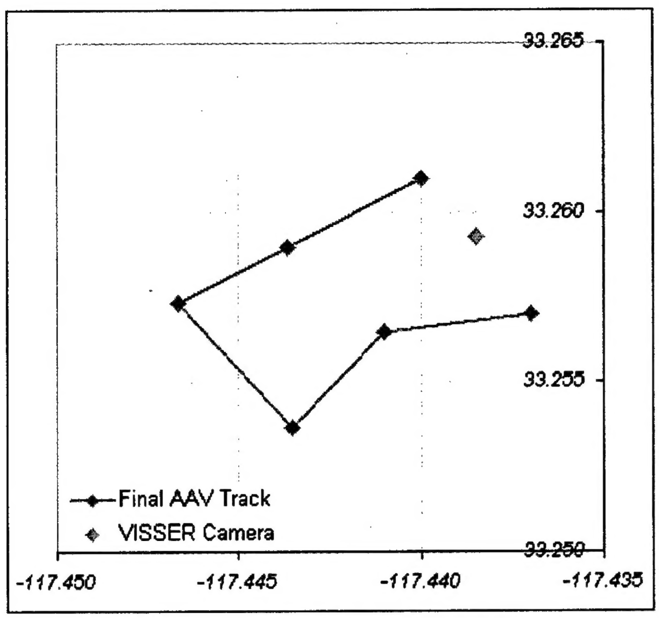

Fig. 8. AAV route at Camp Pendleton, CA

Three AAVs were used during the trials. Each AAV navigated the same course (one at a time), depicted in fig. 8. The original experimental plan called for each AAV to navigate the course with each system (PLGR and the three variations of MM) an equal number of times, in random order, and in both clockwise and

counter-clockwise directions. Due to various AAV difficulties (including power fluctuations on one vehicle and loss of a deflector bolt on another), the total number of runs with usable data was just over 50% of the original plan. Nevertheless, each system configuration was successfully tested on at least four runs, as shown in table 3.

C. Data Collection and Analysis

DGPS positions, start and end timestamps were recorded by the MM system computer along the tracks traversed during demonstration runs. For test cases in which the MM was not to be used, the computer continued to record this data, but the display was turned off. Performance was measured in terms of "cross-track" error (CTE), which is the perpendicular distance in meters between the planned route and the actual track (fig. 9), recorded as a series of latitude and longitude points from the DGPS receiver:

$$CTE_P = \left| \frac{C_X C_Y \left[(Y_E - Y_S)(X_P - X_S) - (X_E - X_S)(Y_P - Y_S)\right]}{\mathrm{SQRT}\left[(C_X(X_E - X_S))^2 + (C_Y(Y_E - Y_S))^2\right]} \right|$$

(X_P,Y_P) = longitude (X) and latitude (Y) of the DGPS point along the vehicle's track,
(X_S,Y_S) = longitude and latitude of the starting point of the planned route segment,
(X_E,Y_E) = longitude and latitude of the ending point of the planned route segment,
C_X = constant to convert longitude into meters (for the average latitude of the course) ≅ 93180.84 m/deg,
C_Y = constant to convert latitude into meters (which is independent of longitude) ≅ 111412.89 m/deg.

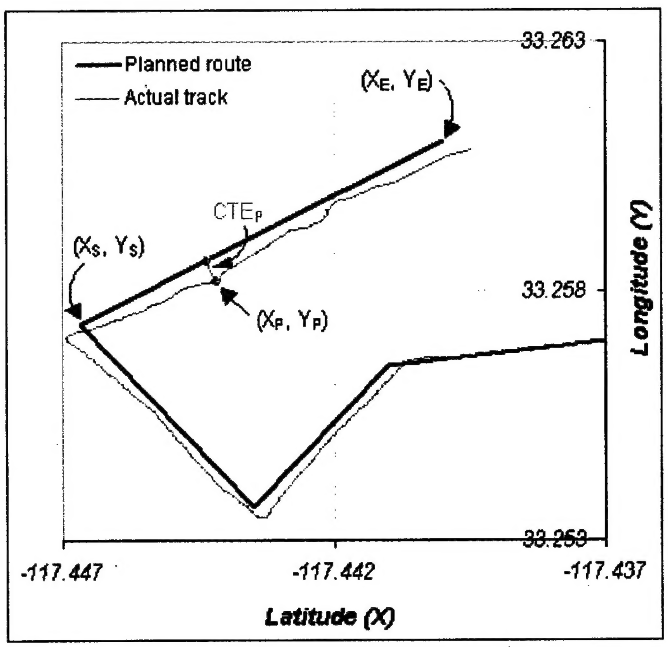

Fig. 9. Cross-track error (CTE).

The CTE for an entire track was calculated as the average of the CTE_P's for all points recorded along the track. The track was broken into turns and straight sections, and average CTE values were calculated separately for each section, for comparison purposes.

The time (in minutes) to complete each run was recorded and compared for different systems. Since the LCU tests used two different courses to avoid interfering boat traffic, the time to complete each LCU run was divided by the average time for the course used before comparing run times by system.

In addition to empirical performance data, informal interviews with craftmasters and navigators were conducted before and after each run to obtain crew feedback, address concerns and answer questions.

IV. RESULTS

A. LCU Results

As shown in fig.10, paper chart (PC) runs required lanes about 1.73 times wider than MM runs for straight legs and about 1.25 times wider during turns. A T-test could not confirm these differences to be significant when comparing CTE values averaged over each track (there were not enough tracks completed for the paper chart case to result in significant results). However, when comparing CTE values for each point along each track (where a new point was recorded every second), a T-test did confirm the differences in lane width to be significant for both straight legs (avg. CTE for PC = 51.42 m, avg. CTE for MM = 29.63, $t = 23.65$, $p < 0.0001$) and during turns (avg. CTE for PC = 38.08 m, avg. CTE for MM = 30.42, $t = 6.14$, $p < 0.0001$). On average, drivers completed the courses in nearly the same amount of time with MM (0.999 x average course time) as with PC (1.003 x average course time).

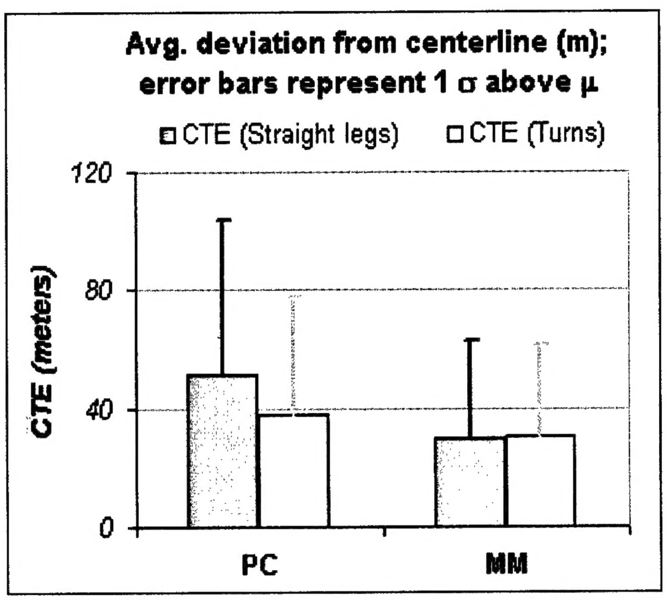

Fig. 10. Summary of LCU tests: paper chart vs. MM.

While using a PC, LCU crew on average required a narrower lane while turning (CTE = 38.08 m) than while driving along straight sections of the course (CTE = 51.42 m), which was not expected. This difference was significant when comparing all points along all PC runs ($t = 5.93$, $p < 0.0001$). With the MM, LCU crew showed no significant difference in average lane width requirements during turns (CTE = 30.81 m) vs. along straight legs (CTE = 31.60 m), even when comparing all points along all MM runs.

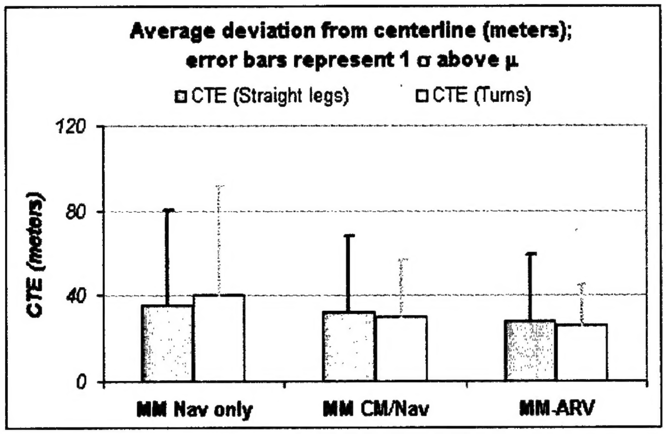

Fig. 11. LCU MM tests, by system configuration.

Fig. 11 compares average CTE for LCU runs using three different MM configurations: use of the MM display in the navigator's station only (*MM Nav only*), use of the MM in both the navigator's and craftmaster's stations (*MM CM/Nav*), and use of MM in both stations plus use of the ARVCOP display in the craftmaster's station (*MM-ARV*). Least squares analysis of all points along all runs indicates that the presence of at least one MM display (i.e., in the navigators station) makes the most significant contribution to the value of average CTE ($F = 139.22$, $p < 0.0001$), followed by the addition of a second MM display in the craftmaster's station ($F = 106.96$, $p < 0.0001$), and the addition of the ARVCOP display ($F = 79.73$, $p < 0.0001$). In other words, the biggest "bang for the buck" – in terms of reducing CTE and, thus, minimizing required lane width – could be realized by implementing at least one MM system on the LCU. Significant improvements would also be made by installing a second MM display (for the craftmaster) and by installing the ARVCOP system on the LCU.

B. AAV Results

As shown in fig. 12, PLGR runs required significantly wider lanes, on average, than did MM runs for both straight legs (CTE for PLGR = 32.78 m, CTE for MM = 10.77 m, $t = 5.24$, $p < 0.0001$) and during turns (CTE for PLGR = 41.85 m, CTE for MM = 10.88 m, $t = 4.61$, $p = 0.0003$). Drivers also required significantly more time to complete the course with PLGR than with MM: average time with PLGR = 13.57 min, average time with MM = 10.52 min ($t = 3.02$, $p < 0.005$).

While using a PLGR, AAV crew on average required a wider lane while turning (CTE = 41.85 m) than while driving on straight legs of the course (CTE = 32.78 m), although a T-test could not confirm this difference to be significant. With the MM, however, AAV crew showed no discernable difference in lane width requirements during turns (CTE = 10.88 m) vs. along straight legs (CTE = 10.77 m). This suggests that the MM assisted crewmembers in anticipating upcoming turns, resulting in more precise lane navigation throughout the course. Comments from crew immediately following the AAV trials confirmed this theory.

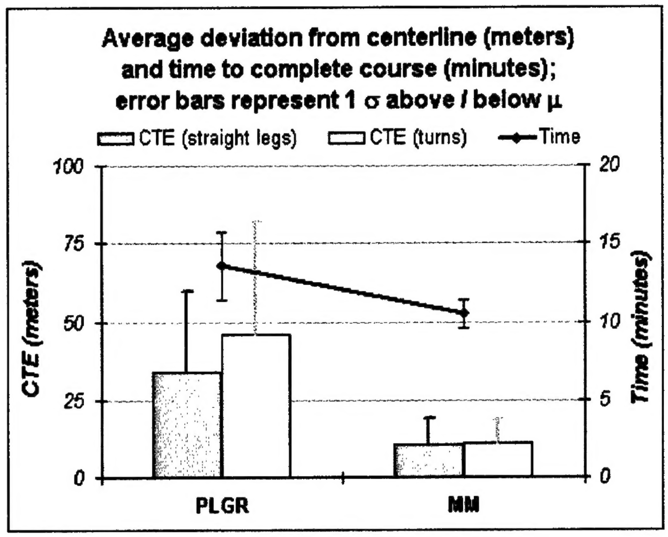

Fig. 12. Summary of AAV tests: PLGR vs. MM.

Neither MM orientation (north-up vs. track-up) nor icon presentation (moving vs. stationary) resulted in any significant performance differences (fig. 13). That is, both CTE and time to complete the course were comparable for all three MM cases.

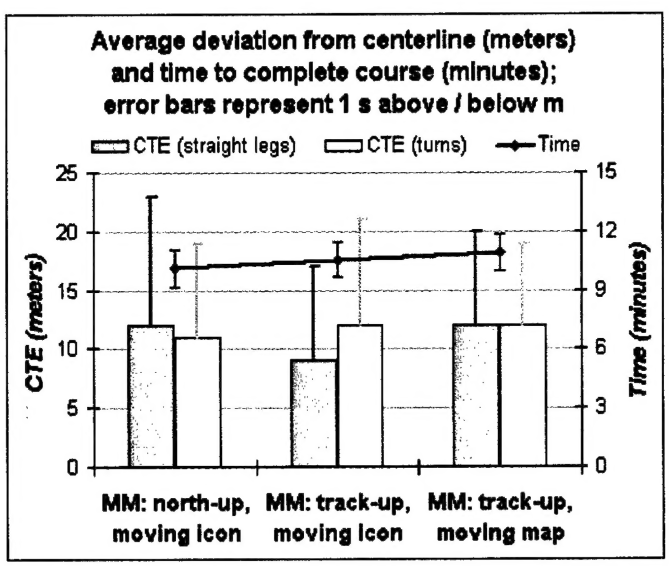

Fig. 13. AAV MM tests, by map orientation (north-up vs. track-up) and presentation (moving icon vs. moving map).

V. CONCLUSIONS AND RECOMMENDATIONS

The minimum lane width required by the vehicles in this study can be approximated in terms of CTE: (μ_{CTE} + $2\sigma_{CTE}$) accounts for approximately 95% of the variability in the track. Therefore, the top of the error bars in figures 10 and 12 provide a reasonable estimate of 50% of the minimum required lane width (i.e., the distance on either side of the center line) for the LCU and AAV platforms used in this study. The following sections refer to both the CTE results and plots of sample runs to make specific recommendations concerning the use of a moving-map display on naval amphibious vehicles and landing craft.

A. LCU Conclusions

The navigator reported that using a paper chart as the sole method of navigating was cumbersome and difficult. A sample plot of that test case (fig. 14) suggests that one of the most difficult tasks under this condition was anticipating turns. In addition, it appears as though the navigator miscalculated the westernmost waypoint (as well as the next waypoint to the north), since that entire route segment was significantly offset from the planned route.

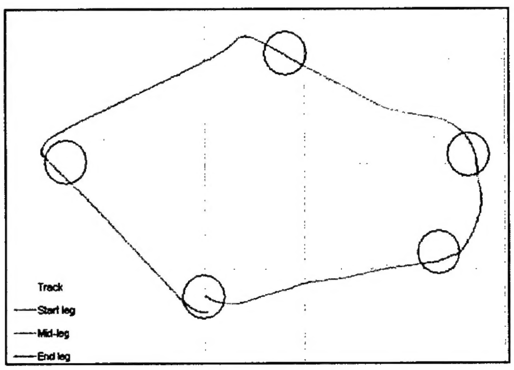

Fig. 14. Sample LCU run with paper chart.

Providing the navigator (but not the craftmaster) with a map display improved the situation by reducing the chance of human error when calculating and navigating to waypoints: all five turns are relatively close to the intended waypoints (fig. 15). The waviness of the northeastern route segment suggests that the helmsman may have had some problems with over-steering, which might have been caused by the delay between the time when the navigator provided course corrections to the craftmaster and the craftmaster relayed his instructions back to the helmsman. Time lags tend to degrade operator performance on tracking tasks (Sanders and McCormick, 1993), possibly causing the over-steering problem shown here.

The sample tracks in fig.s 16-17 and the CTE results in fig. 11 all suggest that providing both the navigator and craftmaster with a common moving-map display results in the most precise navigation along a predefined course. Use of the ARVCOP heads-up system in conjunction with the MM (fig. 17) resulted in slightly better performance than the 2-station MM case.

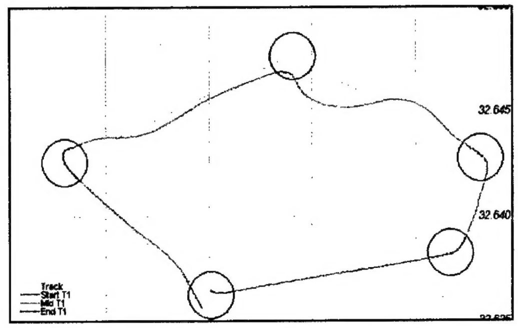

Fig. 15. Sample LCU run with MM (navigator only).

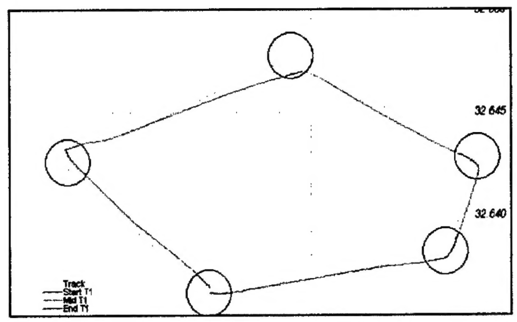

Fig. 16. Sample LCU run with MM in both navigator's and craftmaster's stations.

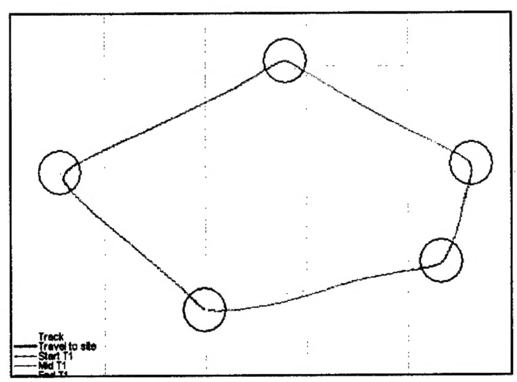

Fig. 17. Sample LCU run with MM in navigator's station and with MM + ARVCOP in craftmaster's station.

B. AAV Conclusions

Drivers with experience using a PLGR were reluctant to accept that the moving-map display might improve their lane navigation performance! However, even the experienced driver of the track shown in fig. 18 experienced a common PLGR problem: missing a waypoint. When a waypoint is accidentally missed while using a PLGR, the driver can only aim for the next waypoint (i.e., there is no way to regain the track until the next waypoint is reached). This is a potentially dangerous situation, since the AAV runs the risk of hitting a mine whenever it is outside the predetermined lane. The longer it remains outside the lane, the more risk it assumes.

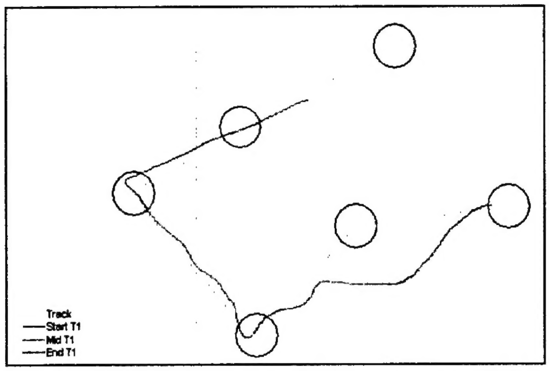

Fig. 18. Sample AAV run with PLGR.

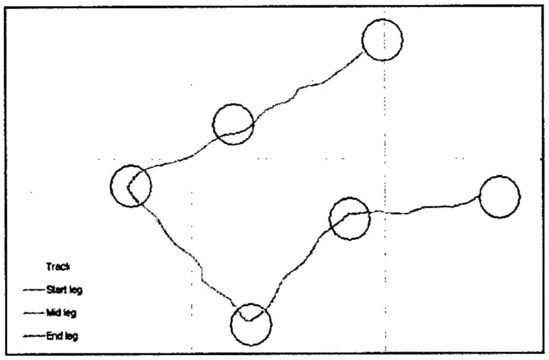

Fig. 19. Sample AAV run with MM.

Both tracks in fig.s 18 and 19 show back-and-forth movements around the centerline. Discussions with the crew revealed that this is a necessary maneuver to cut through waves. If the AAV moves straight forward, its hull would be buried beneath the surface and slow down considerably. Instead, the driver tends to weave back and forth across the surface.

C. Recommendations

The MM system demonstrated by NRL during TH03 significantly improved the navigation performance of LCU and AAV platforms by enhancing crew situational awareness, improving crew communications, and decreasing crew reaction times, compared with existing systems. The plots in fig.s 10 (LCU) and 12 (AAV) reveal significant improvements in CTE (and, thus, a significant reduction in lane width requirements) when driving with the moving-map display vs. a paper chart (for LCU) or PLGR (for AAV). Such a reduction in lane width equates to a corresponding reduction in labor, time, and threat to safety required to clear the lane prior to an assault.

Based on these results, the MIREM team recently recommended in a fleet-wide Navy message (MIREM, 2003) that “some type of graphic navigation system / display should be expedited to the fleet. The system should provide ... clear navigational and situational awareness (craft displayed relative to intended track), direct interface with the craft driver (reduced maneuvering reaction time), and a means to ingest and display EDSS data (minimized error in entry and transfer of information).”

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